

Phytoremediation of Polychlorinated Biphenyl (PCB)-Contaminated Sediment: A Greenhouse Feasibility Study

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ABSTRACT

Contaminated sediments dredged from navigable waterways often are placed in confined disposal facilities to prevent further spread of the pollutants. Reducing contaminants to acceptable levels would allow for disposal of the sediments and further dredging activity. A greenhouse study was conducted to evaluate plant treatments and the addition of an organic amendment to decrease the concentration of PCB congeners found in Arochlor 1260. Sediment treated with the amendment and either low transpiring plants or no plants had the greatest removal of the PCB congeners. High-transpiring plants apparently prevented the highly reducing conditions required for reductive dechlorination of highly chlorinated PCBs. Most likely, the amendment provided labile carbon that initiated the reducing conditions needed for dechlorination. The sediment moisture content and moisture-related plant parameters were significant predictors of the PCB loss. *Carex aquatilis* and *Spartina pectinata* are predicted to be the most effective plant treatments for phytoremediation of PCBs.

POLYCHLORINATED BIPHENYLS (PCBs) were first manufactured in 1881 and became widely used in the United States in 1929. These chemicals have been utilized in a wide variety of applications including transformer oils to facilitate cooling, hydraulic fluids, surface coatings for carbonless copy paper, plasticizers, sealants, caulking, synthetic resins, paints, waxes, and as flame-retardants in lubricating oils (Agency for Toxic Substances and Disease Registry, 2000). The known health effects and recalcitrance of PCBs in the environment resulted in Congress enacting section 6(e) of the Toxic Substances Control Act (TSCA) in 1976. This included prohibitions on the manufacture, processing, and distribution of PCBs. More than 680 000 metric tons of PCBs were manufactured in the United States before cessation of production in 1977 (USEPA, 2006). Polychlorinated biphenyls were manufactured under the trade name Arochlor in the United States, and the most common were Arochlor 1232, 1242, 1254, and 1260. Each Arochlor is composed of 60 to 90 different PCB congeners (Frame et al., 1996). Arochlor 1260 is the most recalcitrant of these compounds (Quensen et al., 1990).

The wide use of PCBs and their resistance to degradation has caused these contaminants to have a broad geographic distribution (MacDonald et al., 2000). Polychlorinated biphenyls have a high affinity for soil,

sediments, colloids, and hydrophobic organic solids (Wijayarathne and Means, 1984; Amellal et al., 2001). Biological remediation is difficult because low water solubility and high partition coefficients (log K_{ow}, log K_{oc}, log K_{om}, etc.) render these compounds unavailable to microorganisms.

The PCB congeners with less than 6 chlorines can be degraded aerobically by common microbial biphenyl dioxygenase enzymes into chlorobenzoic acid but are resistant to degradation under the low redox potentials frequently found in sediments (Price et al., 1999; Ellis et al., 2003). Higher chlorinated biphenyls, such as those found in Arochlor 1260, are resistant to microbial degradation under aerobic conditions but may be dechlorinated under anaerobic conditions. Both reductive dechlorination and aerobic metabolism must occur on contaminated sediments for the highly chlorinated PCBs to be remediated (Master et al., 2002). Reductive dehalogenation typically removes chlorines from the meta (3,3',5,5')- and para-positions (4,4') of the PCBs. This results in lower concentrations of the highly chlorinated PCBs (>6 chlorines) and higher concentrations of the lower chlorinated PCBs (<6 chlorines) in the sediment. These lower chlorinated PCBs are resistant to reductive dechlorination, but are easily degraded under aerobic conditions. Thus, highly chlorinated PCBs require sequential anaerobic and aerobic conditions for complete remediation (Evans et al., 1996; Master et al., 2002).

Wetland plants present a unique possibility of exposing the same sediment to both anaerobic and aerobic conditions. Many wetland plant species possess aerenchyma (Teal and Kanwisher, 1966; Armstrong, 1979; Smirnov and Crawford, 1983), the tissue in the plant that allows the passage of air from the aerial portions to the roots. Thirty to forty percent of the O₂ supplied to the root via the aerenchyma is lost to the rhizosphere (Armstrong, 1979). Reductive dechlorination could occur in bulk sediments with aerobic degradation in the rhizosphere of the wetland plants. Wetland plants increase the redox potential of the rhizosphere in wetland soils (Lin and Mendelssohn, 1999). To our knowledge, no studies have attempted to use plant species to enhance the dissipation of highly chlorinated PCBs from dredged sediments.

The objective of this study was to select plant species and soil amendments that could be used to enhance the loss of highly chlorinated PCBs from a sediment. Several plant species were investigated in the presence and absence of an organic amendment while monitoring ten PCB congeners over time. Seven of these congeners were present in the sediment after it was spiked with Arochlor 1260. The remaining three congeners analyzed were anticipated reductive dechlorination products.

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Published in J. Environ. Qual. 36:239–244 (2007).
Technical Reports: Bioremediation and Biodegradation
doi:10.2134/jeq2006.0089
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MATERIALS AND METHODS

This study evaluates the effects of several plant species (*Carex aquatilis*, *Scirpus fluviatilis*, *Spartina pectinata*, *Tripsacum dactyloides*, and *Morus rubra*) with and without a starch/straw amendment on the dissipation of seven PCB congeners present in Arochlor 1260. The duration of this study was 1.5 yr and was conducted in a greenhouse at Purdue University (West Lafayette, IN, USA).

Sediment, Contaminant, and Treatments

Dredged sediment was obtained from the Kinnickinnic River in Milwaukee, WI in December 2001. The texture of the sediment was a silt loam (61% silt, 5% clay, 34% sand). The physical and chemical properties of the sediment are presented in Table 1 (MDS Harris Laboratory, Lincoln, NE). The sediment was sent to Alpha Analytical Laboratories (Westborough, MA) and found to contain no PCBs. Therefore, transformer oil containing Arochlor 1260 was obtained from Safety-Kleen (Twinsburg, OH). Oil was mixed with acetone to obtain a final concentration of 1000 mg L⁻¹ Arochlor 1260. Exactly 100 mL of this mixture was uniformly sprayed onto 5 kg of the sediment to obtain a total PCB concentration of approximately 20 mg kg⁻¹. A total of 120 5-kg sets of spiked sediment were prepared and taken through two wet-dry cycles. Water was added to obtain approximately 70% of moisture held at the saturation point and then allowed to dry. After three wet-dry cycles, 500 g of unspiked sediment per 5 kg of sediment were added to re-inoculate with soil microbes that may have been lost during the spiking procedure. To half of the sediment (60 sets), an amendment containing 89% straw and 11% starch adjusted with fertilizer to a C/N ratio of 10:1 was added at 1% by weight of the sediment (0.08 kg of amendment per 5 kg sediment).

The sediment was placed in 7.57-liter pots with a polyethylene bag lining each pot. Before planting, water was added to all pots to bring the sediment to saturation and allowed to remain at that moisture content for 3 d after which the plants were planted. Treatments included river bulrush (wetland species) (*Scirpus fluviatilis*), eastern gama grass (terrestrial species) (*Tripsacum dactyloides*), lake sedge (wetland species) (*Carex aquatilis*), and prairie cord grass (wetland species) (*Spartina pectinata*). All pots were fertilized once per month with 2.5 mg kg⁻¹ K and 6.25 mg kg⁻¹ N to provide nutrition for the growing plants. In the amended sediment, all of the *S.*

fluviatilis died. At the end of the anaerobic phase (3.5 mo), this plant was replaced with *Morus rubra*. Each treatment was replicated 4 times on each amendment type.

All pots were maintained at the saturation point during the first 3.5 mo of the experiment. The saturation point for the sediment was determined using the saturated paste method. During the first 9 wk of the experiment, the plants also were evaluated for their ability to dewater the sediment. This was done by watering the plants to the saturation point and monitoring for moisture loss by weighing each pot individually on a weekly basis (Kramer, 1983). After 3 wk of monitoring the moisture loss, the pots were watered to the saturation point again. This process was repeated three times. For the remainder of the first 3.5 mo the pots were watered to the saturation point three times per week. After the completion of the first 3.5 mo of the experiment, the pots were maintained at the field capacity which we defined as one-half the gravimetric moisture content at saturation.

Sampling

After 1.5 yr of growth, the pots were destructively sampled. Root and shoot parameters including root biomass, root length, root surface area and shoot biomass were measured. Root biomass and shoot biomass were quantified by drying plant tissue and weighing. The root length and surface area were obtained by scanning a subsample of the roots with a root scanner (WinRHIZO, Regent Instruments). Sediment samples were taken from each pot at the beginning of the experiment. These samples served as the basis of comparison for the 1.5 yr sediment samples.

Extraction Procedure

Approximately 5 g of the sediment was weighed into a glass scintillation vial, and 25 µL of 1000 mg L⁻¹ Alachlor was added to the sediment as a matrix spike. Fifteen mL of 90:10 tetrahydrofuran (THF)/water (volume/volume) was added. The slurry was then suspended on a vortex mixer for 1 min and placed on a box shaker for 4 h. Ten mL of the extract was placed in a clean scintillation vial containing 5 mL iso-octane and 5 mL nanopure water and placed on a rotator (Glas-Col, Rugged Rotator, Terre Haute, IN) for 24 h. The samples were passed through a dried sodium sulfate column into a gas chromatography (GC) vial, and 0.375 µL of 2000 mg L⁻¹ 2,4,5,6-tetrachloro-m-xylene (TCX) was added as the internal standard. Gas chromatography was used for analysis of the samples and analytical standards using a DB-5 column with an electron capture detector (ECD). Extraction efficiencies with this method were close to 100% and produced statistically identical results to the standard EPA Soxhlet extraction method. For every 30 samples extracted, three samples were replicated and two blanks were included. The PCB concentrations were determined by using the ratio of the PCB congener to the internal standard. The congeners selected for monitoring remediation progress (Table 2) are major congeners in Arochlor 1260 and congeners shown to dechlorinate or accumulate under reducing conditions (Quensen et al., 1990).

Gas Chromatography

The inlet temperature on the GC was 300°C with a pressure of 77.64 kPa and a flow rate of 34.8 mL min⁻¹ for the helium carrier gas. The temperature program for the GC oven started at 40°C for 2 min and then increased 10°C min⁻¹ until reaching 120°C. At this point, the temperature increased 6°C min⁻¹ until 150°C was reached, and then the temperature increased 3°C min⁻¹ until the oven reached 225°C and was held at that

Table 1. Selected physical and chemical properties of the sediment used in this study.

Property	Value†
pH	7.5
Soluble salts, dS m ⁻¹	2.20
Sodium, mg kg ⁻¹	93
Organic matter, %	3.7
Nitrate N, mg kg ⁻¹	64
Phosphorus, mg kg ⁻¹	30
Potassium, mg kg ⁻¹	90
Magnesium, mg kg ⁻¹	250
Calcium, mg kg ⁻¹	3790
Sulfate sulfur, mg kg ⁻¹	547
Zinc, mg kg ⁻¹	86.1
Manganese, mg kg ⁻¹	14.2
Copper, mg kg ⁻¹	15.7
Iron, mg kg ⁻¹	133
Boron, mg kg ⁻¹	0.7
Bulk density, g cm ⁻³	1.0
Cation exchange capacity, cmol _c kg ⁻¹	22
Base saturation, %	65

† Results from MDS Harris Laboratory Analysis on sediment used in greenhouse study.

Table 2. Polychlorinated biphenyl (PCB) congeners chosen for analysis.

Peak #†	IUPAC #‡	ID
1	52	2,2',5,5'-tetrachlorobiphenyl§
2	47	2,2',4,4'-tetrachlorobiphenyl§
3	56	2,3,3',4'-tetrachlorobiphenyl§
4	123	2,3',4,4',5'-pentachlorobiphenyl¶
5	153	2,2',4,4',5,5'-hexachlorobiphenyl¶
6	141	2,2',3,4,5,5'-hexachlorobiphenyl¶
7	138	2,2',3,4,4',5'-hexachlorobiphenyl¶
8	183	2,2',3,4,4',5',6-heptachlorobiphenyl¶
9	180	2,2',3,4,4',5,5'-heptachlorobiphenyl¶
10	170	2,2',3,3',4,4',5-heptachlorobiphenyl¶

† Peak # is the internal number given to the congener in our analysis.

‡ IUPAC number is the number given to the compound by the International Union of Pure and Applied Chemistry.

§ Congeners not present in Arochlor 1260 but are expected degradation products.

¶ Congeners present in Arochlor 1260.

temperature for 10 min. The detector was held at 300°C with a flow rate of 25 mL min⁻¹ for the nitrogen gas. This method is a modification of the method reported in Frame et al. (1996) on a DB-1 column. Splitless injection was used and 1 µL of extract was injected.

Statistics

The experiment was arranged in a randomized complete block design with blocks established along the temperature gradient in the greenhouse. The *S. fluviatilis* and *M. rubra* treatments were compared outside of the full factorial because the *S. fluviatilis* plants died in the amended sediment and were replaced with *M. rubra* 3.5 mo into the experiment; neither plant treatments had both sediment treatments, and therefore, could not be analyzed within the full factorial experiment.

The general linear model (GLM) of ANOVA (SAS Statistical Software, SAS Institute, Cary, NC) was used. Data were log transformed to meet the assumptions of this model. All graphs used back-transformed means to aid in visualization and data interpretation. In addition to analyzing the PCB degradation with treatments as predictors, the moisture contents measured in the initial 9 wk of the study, root and shoot biomass, root length, root surface area, and the moisture content of the sediment at the end of the experiment were used as predictors of the PCB percentage loss using the GLM procedure with SAS as a tool to determine significance and to calculate the least squares means. The level of significance was

$p < 0.05$ in all instances unless stated otherwise. Pairwise correlations between plant and sediment parameters and the percentage loss of PCBs were determined using Spearman rank correlation coefficient as computed by JMP 5.1, another SAS software package. The Pearson product moment correlation was used as a measure of the strength of the linear relationship between two variables with an r value (Sall et al., 2001).

A principle components analysis of the seven PCB congeners was conducted using the principle component analysis (PCA) of SAS.

RESULTS AND DISCUSSION

Polychlorinated Biphenyl Removal

Significant differences between percentage losses of PCBs were found between treatments for some of the PCB congeners, but none of the expected degradation products were detected (limit of quantification 0.1 mg L⁻¹ in solution). Significant differences between treatments were observed for the percentage loss of 2,3',4,4',5'-pentachlorobiphenyl and also for 2,2',3,4,4',5',6-heptachlorobiphenyl. For the 2,2',3,4,4',5',6-heptachlorobiphenyl, *C. aquatilis* with amendment had significantly higher percentage loss than *C. aquatilis* without amendment, *S. pectinata* with amendment, and *T. dactyloides* with amendment (Table 3). In addition, mulberry (*M. rubra*) with amendment had significantly higher percentage loss than did *S. fluviatilis* without amendment.

Percentage loss of 2,3',4,4',5'-pentachlorobiphenyl was greater in the presence of *C. aquatilis* than *S. pectinata* and *T. dactyloides*. Sediment in the presence of *M. rubra* had greater loss of the PCB congeners than the sediment in the presence of *S. fluviatilis*. The percentage loss associated with *C. aquatilis* with the amendment, *M. rubra* with the amendment, and the unplanted control with amendment had the highest percentage loss of all PCB congeners (Table 3). These three plant/amendment combinations had two things in common: (a) all received the sediment amendment, a carbon-rich organic matter added to induce reducing conditions in the sediment in the first part of the experiment, and (b) none of the treatments were efficient in dewatering the sediment (Euliss, 2005).

Table 3. Summary of percentage loss of polychlorinated biphenyl (PCB) congeners and plant treatments. The statistical analysis for mulberry and scirpus was separated from the other treatments because of the necessity to replant these treatments. $n = 4$.

		Congener						
Plant†	Amendment‡	4§	5	6	7	8	9	10
		% loss						
No plants	+	4.17abc	6.12a	11.8a	10.2a	15.5ab	5.26a	9.50a
No plants	—	2.91abc	4.10a	2.49a	5.30a	4.45abcd	3.56a	4.26a
Carex	+	10.2a¶	13.9a	6.77a	6.86a	21.0a	14.3a	15.0a
Carex	—	8.37a	8.34a	3.77a	1.04a	4.04bcd	6.27a	5.87a
Spartina	+	2.62abc	3.78a	1.91a	2.97a	0.52cd	2.78a	3.33a
Spartina	—	1.34bc	2.17a	3.97a	7.89a	0.79bc	2.40a	1.93a
Tripsacum	+	0.49c	0.25a	0.31a	0.98a	0.39d	0.11a	0.61a
Tripsacum	—	5.10ab	5.32a	5.86a	7.96a	5.00abc	5.82a	4.21a
Mulberry	+	8.30A	9.09A	5.63A	8.17A	8.25A	7.92A	5.06A
Scirpus	—	1.55B	1.15A	0.71A	0.95A	0.67B	1.00A	0.91A

† Carex = *C. aquatilis*, Spartina = *S. pectinata*, Tripsacum = *T. dactyloides*, Mulberry = *M. rubra*, Scirpus = *S. fluviatilis*.

‡ + organic amendment added; - organic amendment not added.

§ 4 = 2,3',4,4',5'-pentachlorobiphenyl; 5 = 2,2',4,4',5,5'-hexachlorobiphenyl; 6 = 2,2',3,4,5,5'-hexachlorobiphenyl; 7 = 2,2',3,4,4',5'-hexachlorobiphenyl; 8 = 2,2',3,4,4',5',6-heptachlorobiphenyl; 9 = 2,2',3,4,4',5,5'-heptachlorobiphenyl; 10 = 2,2',3,3',4,4',5-heptachlorobiphenyl.

¶ % differences within a given congener followed by the same letter are not significantly different.

Highly chlorinated PCBs, such as those found in Arochlor 1260, require reductive dechlorination as the first step in remediation, and this process was more complete in treatments with low transpiration and high soil water content. In these treatments, reductive dechlorination would lead to the accumulation of less chlorinated congeners that were possibly lost to aerobic microorganisms during the aerobic stage of the experiment. In the other treatments, the plants were more effective at removing water from the flooded soils and consequently reintroduced at least partially oxidizing conditions. Therefore, the sediment containing high transpiring plants, particularly those with oxygen transport to the roots through aerenchyma, would not be expected to induce reductive dechlorination. Quensen et al. (1990) noted that aerobic mineralization of PCBs is limited to PCBs with five or fewer chlorines. Of the congeners that were monitored in this study, only one had five chlorines present (2,3',4,4',5'-pentachlorobiphenyl). This also was the congener with the smallest number of chlorines detectable in significant amounts in Arochlor 1260 and one of the two congeners to show significant differences in response to treatments. Quensen et al. (1990) did not find any evidence for the aerobic degradation of Arochlor 1260 and did not detect 2,3',4,4',5'-pentachlorobiphenyl. During the dechlorination of Arochlor 1260, penta-, tetra-, tri-, and dichlorobiphenyls accumulate (Bedard et al., 1996; Van Dort et al., 1997). Examining the chlorine distribution of the PCB compounds monitored in this study, the 2,2',3,4,4',5,5'-heptachlorobiphenyl could lose one chlorine from a meta position and become 2,2',4,4',5,5'-hexachlorobiphenyl, which is another one of the congeners present in Arochlor 1260. This is a likely pathway for reductive dechlorination, because reductive dechlorina-

tion preferentially removes chlorines from the meta and para positions (Nies and Vogel, 1990) and could explain why the percentage loss of the 2,3',4,4',5'-pentachlorobiphenyl was not large (Fig. 1).

In sediments maintained at water saturation, reductive dechlorination is likely with possible accumulation of less chlorinated PCBs (Brown and Wagner, 1990; Quensen et al., 1990). Using plant species that remove water from the sediment and introduce oxygen into the rhizosphere through aerenchyma could greatly stimulate removal of lower-chlorinated PCBs from the environment but would have far less impact on higher chlorinated congeners. Tang and Myers (2002) achieved a 40% reduction of PCBs in dredged sediments by periodic tilling of the surfaces, exposing new sediment surfaces to oxygen and light. With plants, oxygen could be introduced into the sediment after initial plant establishment. Quensen et al. (1990) noted that the most complete removal of PCBs during an aerobic phase of an experiment can occur only after a complete reductive dechlorination stage. In this experiment in which Arochlor 1260 was the starting contamination point, the reductive dechlorination stage probably needed to be longer to help stimulate transformation of the congeners. Arochlor 1260 has been noted to be resistant to all remediation efforts, including reductive dechlorination. Quensen et al. (1990) did not observe reductive dechlorination of Arochlor 1260 for 8 wk in a sediment and 24 wk in an additional sediment during incubation under reducing conditions. Dechlorination proceeded very slowly (0.04 to 0.21 μg of chlorine per gram of sediment per week) for the duration of the experiment with 15% of the meta- and para- chlorines removed after 50 wk in a sediment, and 18% of meta- and para-chlorines removed after 16 wk in the other sediment.

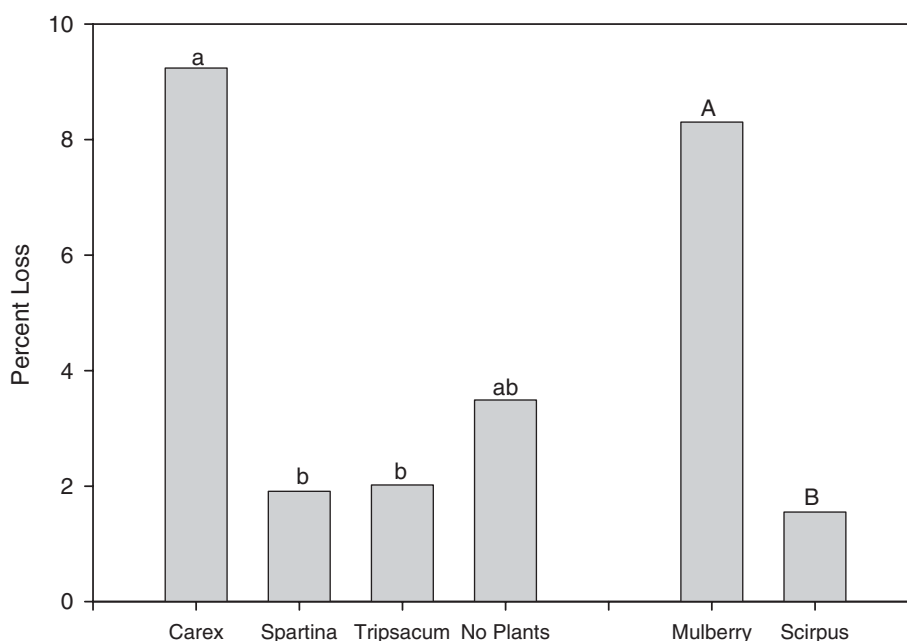


Fig. 1. Back-transformed percentage loss of 2,3',4,4',5'-pentachlorobiphenyl after 1.5 yr of growth. $n = 8$. Bars associated with the same letter are not significantly different ($p < 0.05$). Mulberry and scirpus are not part of the full factorial (capital letters) because mulberry represents the *S. fluviatilis* that died and was replaced by *M. rubra*. $n = 4$.

Plant and Sediment Parameters as Predictors of Polychlorinated Biphenyl Loss

Principle component analysis was performed on all PCB congeners, and the percentage loss was highly correlated among all congeners (Table 4). A mean value was assigned for the average percentage loss across all PCB congeners after 1.5 yr of growth. This variable was predicted for all of the sediment and plant parameter data available. Removing nonsignificant variables from the model individually, the parameters found to be significant predictors of the average PCB loss were shoot biomass, root biomass, root surface area, moisture content after 1.5 yr of growth, and fraction of water lost 7, 28, 35, 42, and 63 d after planting. Shoot biomass was negatively correlated with the PCB loss, but root biomass was positively correlated with the PCB loss, suggesting that high root biomass enhanced degradation. Most of the water-loss parameters were negatively correlated with PCB loss. The average of their contribution to the model was negative, consistent with the previous discussion in which it was suggested that high moisture content (low water loss) was necessary to promote reductive dechlorination. Thus, the lower percentage loss of water (higher the moisture content) from the sediment was associated with greater percentage losses of PCBs.

After the final model was selected, the GLM procedure in SAS was used to generate least squares means to provide predicted population margins; that is, to estimate the marginal means over a balanced population. In essence, this procedure adjusts means for PCB loss to eliminate the impact of other contributing factors (e.g., moisture content, root biomass, shoot biomass). When the significant predictors of PCB loss were adjusted to be equal across all treatments, *C. aquatilis*, *T. dactyloides*, and *S. fluvialilis* without the amendment and *M. rubra* with amendment would have had the highest percentage loss (Table 5). The variability in percentage loss in Table 5 reflects the innate differences among the plant species for PCB degradation. Because most of the predictors that were significant were related to moisture content, these species would be most efficient if the sediment moisture content were similar across all treatments. *T. dactyloides* and *M. rubra* could be removed

Table 4. Correlation matrix for percentage loss of polychlorinated biphenyl (PCB) congeners with each other generated using principle components analysis.

PCB	PCB						
	4†	5	6	7	8	9	10
	r^2						
4	1	0.986	0.957	0.927	0.791	0.948	0.961
5	—	1	0.964	0.952	0.808	0.978	0.968
6	—	—	1	0.952	0.847	0.949	0.979
7	—	—	—	1	0.809	0.952	0.953
8	—	—	—	—	1	0.825	0.839
9	—	—	—	—	—	1	0.969
10	—	—	—	—	—	—	1

† 4 = 2,3',4,4',5'-pentachlorobiphenyl; 5 = 2,2',4,4',5,5'-hexachlorobiphenyl; 6 = 2,2',3,4,5,5'-hexachlorobiphenyl; 7 = 2,2',3,4,4',5'-hexachlorobiphenyl; 8 = 2,2',3,4,4',5',6-heptachlorobiphenyl; 9 = 2,2',3,4,4',5,5'-heptachlorobiphenyl; 10 = 2,2',3,3',4,4',5-heptachlorobiphenyl.

Table 5. Percentage polychlorinated biphenyl (PCB) loss (as determined by least squares means) after the significant predictors of PCB loss were adjusted to be equal across all treatments.

Plant	Amendment	Loss (%)
Carex	+	-2.72
Spartina	+	3.21
Mulberry	+	8.09
No plants	+	-9.75
Tripsacum	+	-3.22
Carex	—	17.36
Spartina	—	18.43
Scirpus	—	11.92
No plants	—	-3.98
Tripsacum	—	21.01

from this list because they were not tolerant to prolonged flooded conditions. Both *S. pectinata* and *C. aquatilis* were able to thrive under flooded conditions and hold great promise for enhancing PCB removal from contaminated sediments.

Pairwise Correlations

An analysis using Pearson's product moment pairwise correlations yielded slightly different plant species and sediment parameters that are most important in predicting the PCB removal. In all treatments except *M. rubra* and *T. dactyloides* sediment moisture content after 1.5 yr of growth and/or the fraction of water lost at various intervals after planting was highly correlated with the PCB removal from the sediment (Table 6). The fraction of water lost in the early part of the experiment was negatively associated with PCB loss, and the sediment moisture content after 1.5 yr of growth was positively associated with the PCB loss. These results were similar to the other results obtained in this study in that the higher moisture content treatments were associated with the highest percentage loss of PCBs. In the case of *M. rubra*, only plant parameters had high correlations: shoot biomass, root biomass, root surface area, and root length. *M. rubra* has been shown to release exudates that support the growth of PCB-degrading bacteria (Leigh et al., 2002). The *M. rubra* was not planted until after the first 3.5 mo of the experiment, so it was associated with high moisture contents in the initial part of the study.

Table 6. Plant and soil parameters significantly correlated ($p < 0.15$) with percentage polychlorinated biphenyl (PCB) loss.

Plant	Amendment	Plant and soil parameters
Carex	+	sediment moisture content after 1.5 yr of growth
Carex	—	water lost 7, 14, 21, 28, 35, 42 d after initiation of experiment.
Spartina	+	water lost 7, 28, 35, 42, 49, 56, 63 d after initiation of experiment.
Spartina	—	root biomass, moisture content after 1.5 yr of growth
Mulberry	+	shoot and root biomass, root length
Scirpus	—	†
No plants	+	water lost 49, 56 d after initiation of experiment
No plants	—	sediment moisture content after 1.5 yr of experiment, fraction of water lost 35 and 42 d after initiation of experiment
Tripsacum	+	†
Tripsacum	—	†

† No significant factors.

However, this species could not grow under saturated conditions. Some of the other species that emerged from this study might be more useful if remediation of the PCBs is attempted under anaerobic conditions.

CONCLUSIONS

The plant species that dewatered the sediment most effectively also inhibited the progress of PCB phyto-remediation for the sediment contaminated with Arochlor 1260. Even with a 3-mo anaerobic stage, those plant treatments associated with the greatest removal of water from the sediments most effectively apparently prevented the highly reducing conditions needed to stimulate the reductive dechlorination of the highly chlorinated congeners found in Arochlor 1260. Significant losses of PCB congeners were observed only in those treatments that resulted in low transpiration rates, high water contents, and lower oxygen available to serve as the terminal electron acceptor. In these treatments, reductive dechlorination was more complete and resulted in lower concentrations of highly chlorinated compounds entering the aerobic phase of the experiment.

Because saturated, PCB-contaminated sediments in the field may be subjected to frequent reductive dechlorination, the introduction of high transpiring wetland plants in these environments may enhance the degradation of the lower chlorinated PCBs that are products of anaerobiosis. In addition, our least squares means test demonstrated that plant treatments *S. pectinata* and *C. aquatilis* should be particularly effective at enhancing the degradation of these compounds under saturated conditions.

REFERENCES

- Agency for Toxic Substances and Disease Registry. 2000. Toxicological profile for polychlorinated biphenyls (PCBs). U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA.
- Amellal, N., J.M. Portal, T. Vogel, and J. Berthelin. 2001. Distribution and location of polycyclic aromatic hydrocarbons (PAHs) and PAH-degrading bacteria within polluted soil aggregates. *Biodegradation* 12:49–57.
- Armstrong, W. 1979. Aeration in higher plants. *Adv. Bot. Res.* 7:225–332.
- Bedard, D.L., S.C. Bunnell, and L.A. Smullen. 1996. Stimulation of microbial para-dechlorination of polychlorinated biphenyls that have persisted in Housatonic river sediment for decades. *Environ. Sci. Technol.* 30:687–694.
- Brown, J.F., and R.E. Wagner. 1990. PCB movement, dechlorinated, and detoxification in the Acushnet estuary. *Environ. Toxicol. Chem.* 9:1215–1233.
- Ellis, L.B.M., B.K. Hou, W. Kang, and L.P. Wackett. 2003. The University of Minnesota biocatalysis/biodegradation database: Post-genomic datamining. *Nucleic Acids Res.* 31:262–265.
- Euliss, K.W. 2005. Dewatering and remediation of contaminated dredged sediments. Ph.D. diss. Purdue Univ., West Lafayette, IN.
- Evans, B.S., C.A. Dudley, and K.T. Klasson. 1996. Sequential anaerobic-aerobic biodegradation of PCBs in soil slurry microcosms. *Appl. Biochem. Biotechnol.* 57–8:885–894.
- Frame, G.M., R.E. Wagner, J.C. Carnahan, J.F. Brown, Jr., R.J. May, L.A. Smullen, and D.L. Bedard. 1996. Comprehensive, quantitative, congener-specific analyses of eight Aroclors and complete PCB congener assignments on DB-1 capillary GC columns. *Chemosphere* 33:603–623.
- Kramer, P.J. 1983. *Water Relations of Plants*. Academic Press, New York, NY.
- Leigh, M.B., J.S. Fletcher, X. Fu, and F.J. Schmitz. 2002. Root turnover: An important source of microbial substrates in rhizosphere remediation of recalcitrant contaminants. *Environ. Sci. Technol.* 36:1579–1583.
- Lin, Q., and I.A. Mendelsohn. 1999. Louisiana applied and educational oil spill research and development program. OSRADP Tech. Rep. Ser. 98-005. OSRADP, Baton Rouge, LA.
- MacDonald, R.W., L.A. Barrie, T.F. Bidleman, M.L. Diamond, D.J. Gregor, R.G. Semkin, W.M.J. Strachan, Y.F. Li, F. Wania, M. Alae, L.B. Alexeeva, S.M. Backus, R. Bailey, J.M. Bewers, C. Gobeil, C.J. Halsall, T. Harner, J.T. Hoff, L.M.M. Jantunen, W.L. Lockhart, D. Mackay, D.C.G. Muir, J. Pudykiewicz, K.J. Reimer, J.N. Smith, G.A. Stern, W.H. Schroeder, R. Wagemann, and M.B. Yunker. 2000. Contaminants in the Canadian Arctic: Five years of progress in understanding sources, occurrence, and pathways. *Sci. Total Environ.* 254:93–234.
- Master, E.R., V.W.M. Lai, B. Kuipers, W.R. Cullen, and W.M. Mohn. 2002. Sequential anaerobic-aerobic treatment of soil contaminated with weathered aroclor 1260. *Environ. Sci. Technol.* 36:100–103.
- Nies, L., and T.M. Vogel. 1990. Effects of organic substrates on dechlorination of arachlor 1242 in anaerobic sediments. *Appl. Environ. Microbiol.* 56:2612–2617.
- Price, R.A., C.R. Lee, and J.W. Simmers. 1999. Phytoreclamation of dredged material: A working group summary. DOER Technical Notes Collection (TN-DOER-C9). U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Quensen, J.F., III, S.A. Boyd, and J.M. Tiedje. 1990. Dechlorination of four commercial polychlorinated biphenyl mixtures (Aroclor) by anaerobic microorganisms from sediments. *Appl. Environ. Microbiol.* 56:2360–2369.
- Sall, J., A. Lehman, and L. Creighton. 2001. *JMP Start Statistics*. Duxbury Press, Pacific Grove, CA.
- Smirnov, N., and R.M.M. Crawford. 1983. Variation in the structure and response to flooding of root aerenchyma in some wetland plants. *Ann. Bot.* 51:237–249.
- Tang, N.H., and T.E. Myers. 2002. PCB removal from contaminated dredged material. *Chemosphere* 46(3):477–484.
- Teal, J.M., and J.W. Kanwisher. 1966. Gas transport in the marsh grass *Spartina alterniflora*. *J. Exp. Bot.* 17:355–361.
- USEPA. 2006. Polychlorinated biphenyls (PCBs): Health effects [Online]. Available at <http://www.epa.gov/opptintr/pcb/pubs/effects.html> (accessed 26 Jan. 2006; verified 30 Aug. 2006). USEPA, Washington, DC.
- Van Dort, H.M., L.A. Smullen, R.J. May, and D.L. Bedard. 1997. Priming microbial meta-dechlorination of polychlorinated biphenyls that have persisted in Housatonic River sediments for decades. *Environ. Sci. Technol.* 31:3300–3307.
- Wijayarathne, R.D., and J.C. Means. 1984. Sorption of polycyclic aromatic hydrocarbons by natural estuarine colloids. *Mar. Environ. Res.* 14:77–89.